

# A Physical Insight into Counter-Rotating Open Rotor In-Plane Loads

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## Résumé :

*Ce papier présente la comparaison des résultats obtenus à l'aide de deux codes de simulation aérodynamique de différents degrés de précision et coût de calcul sur le cas d'un moteur à doublet d'hélices contrarotatives (AI-PX7). Le principal but étant d'évaluer la capacité d'un code basé sur la méthode des singularités à prédire à la fois les performances globales des rotors, les efforts dans le plan hélice et la distribution des efforts sur pale au long d'un tour. De plus, l'ajout de modèles d'effets d'installation et d'aérodynamique de profil instationnaire ont servi aussi à évaluer des possibles améliorations de ces prédictions initiales.*

## Abstract :

*This paper presents the comparison of results obtained from two codes with different degrees of accuracy and computational time on the case of a counter-rotating open rotor (AI-PX7). The main goal was to assess the capacity of a code based on singularity methods to predict global propeller performance, the in-plane loads, and the blade load distribution during a full blade cycle. Moreover, installation and unsteady correction models have been added in order to evaluate the possible improvements of initial predictions.*

**Mots clefs :** Open Rotor; In-Plane Loads; Unsteady Thin-Airfoil Theory

## 1 Introduction

A code-to-code assessment between an accurate CFD solver (*elsA* [2]) and an unsteady lifting-line code (HOST [1]) is presented. The test case used for comparison is an Airbus generic counter-rotating open rotor geometry AI-PX7 at high-speed conditions and at 1° of incidence. Propeller performance, blade loading, and induced velocity fields over a revolution are compared, in order to show the strengths and weaknesses of lifting-line codes.

HOST was conceived by Eurocopter as a comprehensive code for the aeromechanical simulation of helicopters. It uses a modular structure in order to be able to simulate from an isolated rotor to a “complete” helicopter. This modular structure makes it easier to extend the use of HOST to other applications such as single and counter-rotating propellers. The aerodynamic computations in HOST use a method based on the lifting-line theory, a singularity method for which the blade is reduced to its quarter-chord line. In the results hereafter, induced velocities from the wake and the surrounding blades are calculated using MINT, a high-order free-wake module developed by Onera [7].

As it has been detailed in a previous conference [5], an unsteady airfoil model for curved and swept

blades has been implemented in **HOST**. This simple model is based on the unified lifting-line theory developed by Guermond and Sellier [6] and adapted to numerical applications by Devinant [3]. The global problem is solved by matched asymptotic expansions between the outer domain, a classical lifting-line problem, and the inner domain, the airfoil and its wake at the considered blade station. The inner domain is solved using a linearized unsteady thin-airfoil theory [8] which adds, to quasi-steady airfoil polar data, the extra lift produced by the plunging and pitching motion of a infinite-span flat plate and its near wake.

Moreover, the effect of the nacelle on the blade aerodynamics can be taken into account in **HOST** thanks to a velocity perturbation field, obtained from a blade-off nacelle *elsA* simulation.

## 2 Test Case Description

Figure 1 shows the AI-PX7 Open Rotor geometry<sup>1</sup> used in the present study. Table 1 presents the main geometrical characteristics and the flight conditions of the considered case.

Four different simulations are presented in this paper: one *elsA* computation performed by François [4] and three different **HOST** simulations, in order to assess the impact of installation effects and unsteady corrections. While the *elsA* computation was performed with a  $0.5^\circ$  time-step, **HOST** simulations were performed with a  $2^\circ$  time-step, for a matter of reasonable computational costs in a design process. In fact, the computational cost of **HOST** simulations are of the order of  $O(t_{\text{step}}^3)$  due to the simulation time,  $O(t_{\text{step}})$ , and the free-wake convection,  $O(t_{\text{step}}^2)$ , where  $t_{\text{step}}$  is the time-step. Moreover, as no interpolation is needed between rotors, the wake propagation is less sensitive to time-step in **HOST** simulations than in *elsA* computations. Thus, a  $2^\circ$  time-step simulation has proven to be a good compromise to capture the main part of the interaction between rotors.

**HOST** “isolated” simulation considered only the propeller blades, but no nacelle was taken into account. The so-called “installation effects” take it into account by introducing a steady velocity perturbation field for both rotors. This field is obtained from a previous *elsA* simulation of the nacelle in blades-off configuration. Finally, “unsteady corrections” stand for the addition of new terms in the airfoil lift calculation so as to consider its unsteady motion and three-dimensional blade forms.

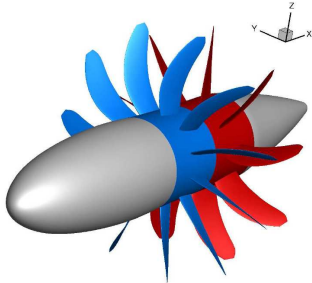


Figure 1: AI-PX7 Geometry

Blade count ( $B_{FR}$ , $B_{RR}$ )	[-]	$11 \times 9$
Front Rotor Diameter	[m]	4.2672
Rear Rotor Cropping	[-]	10%
Rotor-Rotor Spacing	[m]	0.95
Mach Number	[-]	0.73
RPM	$[\text{min}^{-1}]$	795, -795
Incidence	$[\circ]$	1.0

Table 1: AI-PX7 Case Conditions

## 3 Code Assessment: Comparison between *elsA* and **HOST**/MINT

This section presents the main results obtained with **HOST** and compared with the reference simulation using *elsA*. First, propeller performance are presented, then global blade thrust is compared, and finally, the blade thrust distribution is presented, i.e. the contribution of each section to the thrust.

**Open Rotor Performance.** Table 2 shows the propeller performance comparison between *elsA* simulation and three **HOST** simulations: “isolated”, with installation effects, and with both installation and unsteady corrections. For **HOST** simulations, pitch angles have been adapted in order to obtain the same global thrust levels  $T = T_{FR} + T_{RR}$  and power ratio  $P_{FR}/P_{RR}$  than *elsA*. Acceptable pitch

<sup>1</sup>AI-PX7, an 11x9-blades Counter-Rotating Open Rotor is an Airbus’ reference configuration for the European SFWA/CleanSky project

		elsA CFD	$\Delta$ Isolated	$\Delta$ w/Installation	$\Delta$ w/Inst+Unst
$\theta^{\text{FR}}$	$[\circ]$	62.50	-1.22 $^\circ$	-1.36 $^\circ$	-1.36 $^\circ$
$\theta^{\text{RR}}$	$[\circ]$	62.50	-0.28 $^\circ$	-0.17 $^\circ$	-0.17 $^\circ$
Thrust	[N]	20320	0.575%	0.458%	-0.87%
Power Ratio		1.25	1.46%	0.893%	0.00%

Table 2: AI-PX7 Performance. Comparison between *elsA* and HOST/MINT results (isolated, installed and installed+unsteady)

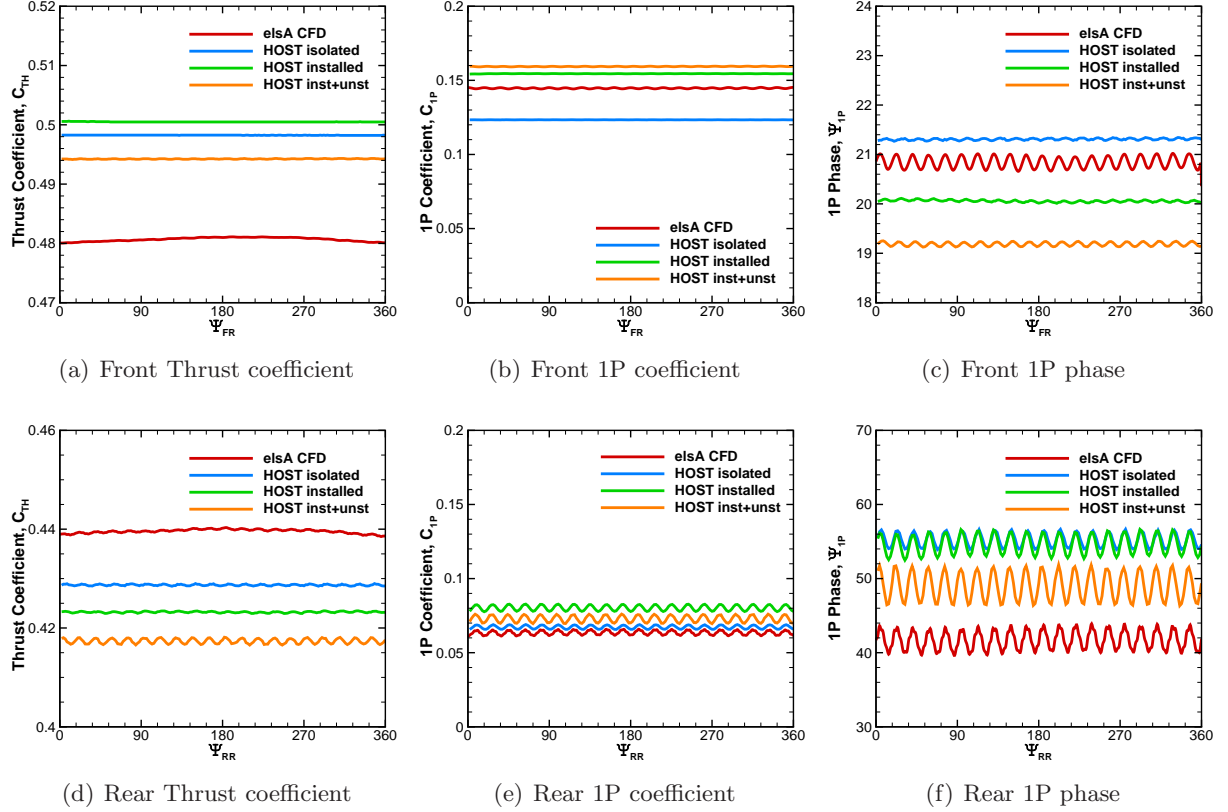


Figure 2: Front and Rear Rotor performance comparison

angle modifications, i.e. around  $1^\circ$ , are required in order to achieve thrust and power ratio target levels. These pitch angles are going to be used in the rest of the paper for comparing different cases.

**Rotor Performance and In-Plane Loads.** Figure 2 shows the thrust coefficient, the in-plane loads coefficient and the in-plane phase lag for front and rear rotors respectively. These parameters are defined as follows:

$$\begin{aligned}
 C_{\text{TH}}^{\text{FR}} &= \frac{T_{\text{FR}}}{\rho_\infty N_{\text{FR}}^2 (2R_{\text{FR}})^4} \quad ; \quad C_{\text{1P}}^{\text{FR}} = \frac{\sqrt{F_{Y_{\text{FR}}}^2 + F_{Z_{\text{FR}}}^2}}{\rho_\infty N_{\text{FR}}^2 (2R_{\text{FR}})^4} \quad ; \quad \phi_{\text{1P}}^{\text{FR}} = \arctan \frac{F_{Y_{\text{FR}}}}{F_{Z_{\text{FR}}}} \\
 C_{\text{TH}}^{\text{RR}} &= \frac{T_{\text{RR}}}{\rho_\infty N_{\text{FR}}^2 (2R_{\text{FR}})^4} \quad ; \quad C_{\text{1P}}^{\text{RR}} = \frac{\sqrt{F_{Y_{\text{RR}}}^2 + F_{Z_{\text{RR}}}^2}}{\rho_\infty N_{\text{FR}}^2 (2R_{\text{FR}})^4} \quad ; \quad \phi_{\text{1P}}^{\text{RR}} = \arctan \frac{F_{Y_{\text{RR}}}}{F_{Z_{\text{RR}}}}
 \end{aligned} \tag{1}$$

Several remarks can be done on these figures. First, the total thrust level is obtained with a slight overestimation of the front rotor thrust (+3.5%) and a slight underestimation of the rear one (-3.5%). These differences can be explained by a lack of slipstream from the rear rotor on the front rotor. Indeed, as HOST is based on the lifting-line theory, the blade is reduced to the quarter-chord line, and thus

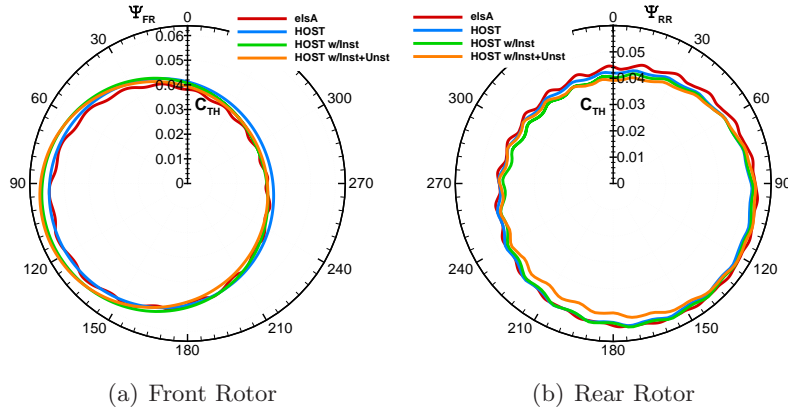


Figure 3: Blade loading along a cycle. *elsA* compared to HOST simulations

chord effects are not well captured. In this open rotor configuration, even if results are still satisfactory, this deficiency starts to appear.

When comparing in-plane loads, it can be noticed how installation effects play an important role in predicting better its magnitude, i.e. differences are reduced from  $-17\%$  to  $+10\%$  for the worst case. Rear rotor in-plane loads magnitude is slightly modified.

Rear rotor in-plane phase lag mean values are closer to *elsA* results when using the unsteady airfoil model, i.e. from  $+12^\circ$  to  $+7^\circ$ . Oscillation amplitude, however, is slightly overestimated. On the other side, the offset of front rotor phase lag is increased due to installation effects and the unsteady model, but values are still in the level of resolution of the simulations,  $2^\circ$ .

**Blade thrust.** Figure 3 plots the blade thrust evolution along a cycle. It compares *elsA* computation with the three HOST simulations. Notice that the thrust coefficient is slightly overestimated in the downward moving blade when adding installation effects, whereas isolated simulation underestimates it in the upward moving blade. Notice also the lack of oscillations in the front blade loads. It can be explained by the fact that lifting-line methods reduce the blade to its quarter-chord line, losing all chordwise information. As the front quarter-chord line is further from the rear rotor than its trailing edge, effects from rear rotor are not captured.

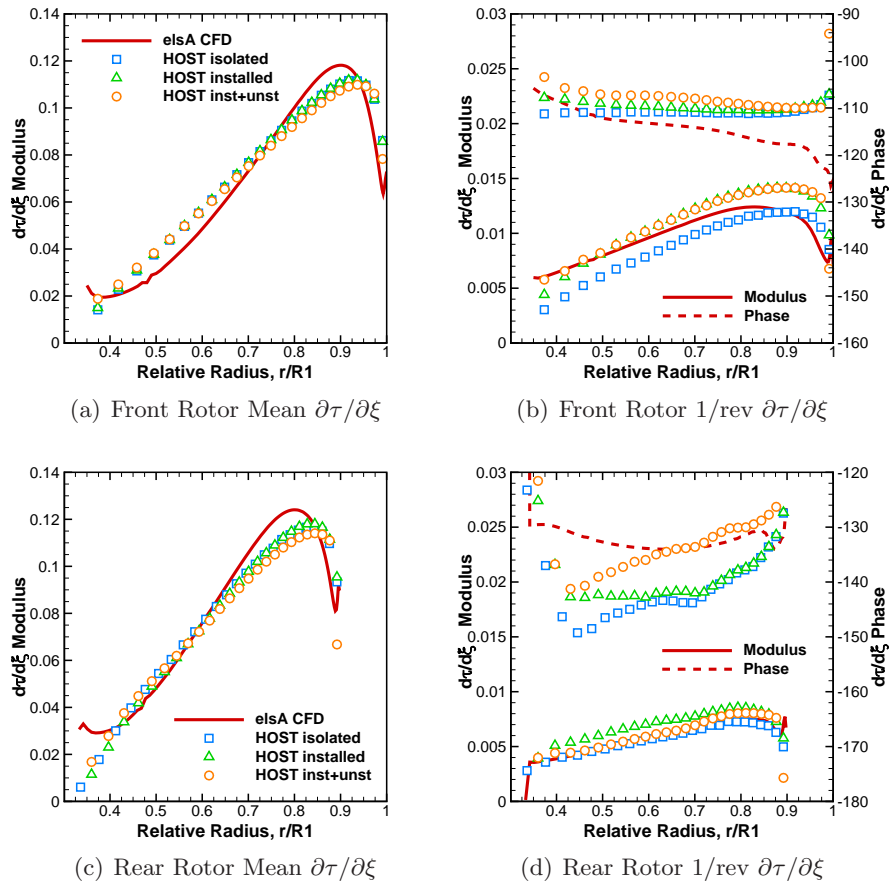
When observing rear blade loads, a slight underestimation appears in the upper part of the blade cycle for all HOST simulations. Moreover, unsteady corrections tend to underestimate them also between  $150^\circ$  and  $240^\circ$ . In rear blades oscillations are captured due to the passage of the front wake across the rear rotor. Notice however that a certain phase lag appears between the peaks, which is due to the point of emission of the wake panels: while in *elsA* they are convected from the trailing edge, HOST does it from the quarter-chord line.

**Blade thrust distribution.** Figure 4 shows the thrust coefficient distribution along the blade  $\partial\tau/\partial\xi$  for the same four simulations. Thrust coefficient distribution is defined as follows:

$$\frac{\partial\tau_{FR}}{\partial\xi_{FR}} = \frac{\partial T_{FR}}{\partial\xi_{FR}} \frac{R_{FR}}{\rho_\infty N_{FR}^2 (2R_{FR})^4} ; \quad \frac{\partial\tau_{RR}}{\partial\xi_{RR}} = \frac{\partial T_{RR}}{\partial\xi_{RR}} \frac{R_{RR}}{\rho_\infty N_{FR}^2 (2R_{FR})^4} \quad (2)$$

Left-hand figures show an important wall effect on the front and rear mean blade loads, which is not captured by HOST as no hub model is implemented, i.e. circulation is imposed to zero at the root section. In the central part of the blade,  $\partial\tau/\partial\xi$  is overestimated. Finally, the blade maximum loading is underestimated and slightly closer to the blade tip. No significant difference is observed between HOST simulations.

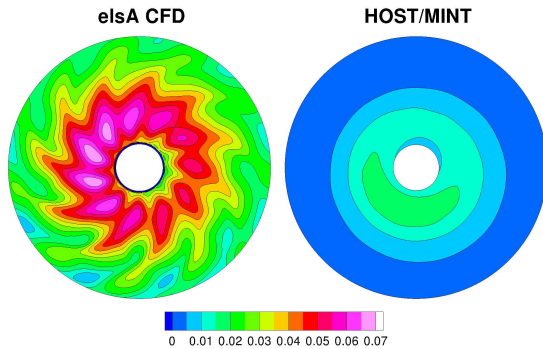
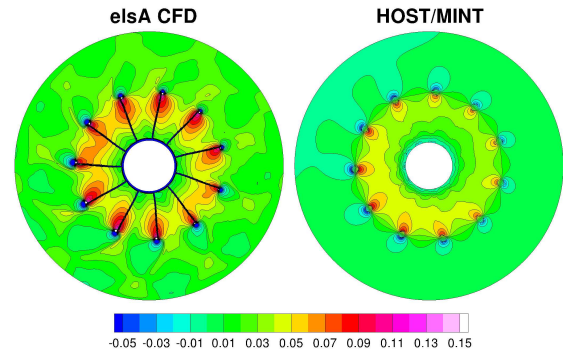
Right-hand side figures show the first mode of  $\partial\tau/\partial\xi$ . Installation effects increase these oscillations on both rotors. The unsteady model corrects slightly the modulus on the rear blade and reduces the phase lag, getting significantly closer to *elsA* results in an important part of the blade.

Figure 4: Discrete Fourier Transform of the Front and Rear Rotor  $\partial\tau/\partial\xi$ 

**Induced Velocity Fields.** This paragraph compares the axial induced velocity as predicted by *elsA* and HOST for two planes normal to the rotating axis: one upstream the front rotor and the other between the rotors.

For the plane upstream the front rotor (see figure 5), important mismatches are observed. Nevertheless, as it has been shown in the previous paragraph, the comparison between blade loads predicted by *elsA* and HOST are very similar. To explain this it must be considered that the upstream plane is very close to the leading edge of the blade, and so the passage of the blade is very well captured in *elsA*. It is not the case in HOST, as the blade is reduced to its quarter-chord line.

In figure 6, even if some differences can be observed, the general pattern is the very well captured by HOST. As HOST considers a potential wake, no velocity deficit is observed due to the viscous effects in the wake. Moreover, similar to what was observed for rear rotor blade loads, a certain phase lag in the tip vortex position can be observed due a difference in the emission points of the wake.

Figure 5:  $u_{\infty x}/V_{\infty}$  upstream front rotorFigure 6:  $u_{\infty x}/V_{\infty}$  between rotors



## 4 Conclusions

A detailed comparison between *elsA* CFD solver and HOST code based on the lifting-line theory, has been done on a generic counter-rotating open rotor geometry AI-PX7 at high-speed conditions and at  $1^\circ$  of incidence. Three different types of HOST simulations have been performed in order to assess the impact of nacelle effects and unsteady corrections on aerodynamic performance and in-plane loads.

Total thrust and power ratio target values have been achieved for all HOST simulations within reasonable pitch angles modifications, i.e.  $\pm 2^\circ$ . On the one hand, offsets obtained in in-plane loads modulus have been reduced when adding the effect of the nacelle. On the other hand, the unsteady airfoil model implemented in HOST allows reducing mismatches on the rear rotor in-plane loads phase lag.

Global blade thrust comparisons put forward some deficiencies of the present method in the prediction of rear potential effect on the front rotor. This phenomenon has been explained by the fact that chord effects are neglected in lifting-line methods.

In the comparisons of thrust distribution along the blade, important mismatches were noticed mainly near the blade root, due to the wall effect. Slight differences in the peak of mean load were also observed ( $-8\%$ ) and its position was closer to the blade tip than in *elsA* simulations. First harmonic thrust distribution was however well captured by HOST simulations, mainly on the rear rotor thanks to the unsteady corrections.

Finally, induced velocity fields have shown, on one side, the impact of neglecting chord effects in HOST and, on the other side, the capacity to capture correctly the potential effect of the tip vortices.

Future works will be devoted to the analysis of auto- and mutually-induced velocities, in order to determine its impact on the generation of in-plane loads (modulus and phase lag).

Moreover, a coupling between HOST simulations and an *elsA* near-wall mesh is being developed in order to obtain a moderate-cost methodology that takes into account three-dimensional, chord, compressibility, and viscosity effects in open rotor simulations.

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